Journal of Materials Processing Technology 243 (2017) 100–111

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Study on the ridge grooves deformation of double-ridged waveguide tube in rotary draw bending based on analytical and simulative methods

Honglie Zhang, Yuli Liu*, He Yang

State Key Laboratory of Solidification Processing, School of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form 8 December 2016
Accepted 9 December 2016
Available online 11 December 2016

Keywords:
Double-ridged waveguide tube
Rotary draw bending
Ridge grooves deformation
Analytical method
Simulative method

ABSTRACT

Cross sectional deformation of double-ridged waveguide tube easily occurs in rotary draw bending due to its structural features of hollowness, thin-wall and shape complexity. Particularly, the ridge grooves deformation would largely affect the transmission characteristics of double-ridged waveguide tube. Thus, using plasticity deformation theory, an analytical method to investigate the ridge grooves deformation is proposed, in which the ridge grooves deformation is considered to be resulted from three parts of deformation, including flange sagging, web deflection and variation of flange width. Then, the analytical method is verified by a FE model from various viewpoints. Finally, the contribution of every part to the ridge grooves deformation under different conditions is analyzed combining analytical and simulative methods. The results show that: (1) The contribution of flange sagging to the width deformation of outer and inner ridge grooves is usually far small and can be omitted. The web deflection results in the decrease of width deformation of outer ridge groove, but the variation of flange width increases that. The web deflection and variation of flange width all lead to the increase of width deformation of inner ridge groove. (2) With the increase of bending angle, the width deformation of outer ridge groove changes little while the absolute value of width deformation of inner ridge groove increases. When the bending radius decreases, the absolute value of width deformation of outer and inner ridge grooves all increase. With the increase of core number, the width deformation of outer ridge groove changes from shrinking to widening while there is no change for the width deformation of inner ridge groove.

1. Introduction

Waveguide tubes have significant application in radar, space communication, electronic countermeasure and remote sensing as millimeter-wave radiation source with advantages of stability, reliability, high-power capability and broad bandwidth (Xue et al., 2015). Moreover, the ridged waveguide tube has a longer cutoff wavelength, a wider bandwidth and lower characteristic impedance, making it have been widely used in microwave and millimeter wave devices (Chen et al., 2013). For the double-ridged waveguide tube, the cross sectional deformation occurs inevitably in rotary draw bending due to its structural features of hollowness, thin-wall and shape complexity, especially for the part of two ridge grooves. When the microwave is transmitted in ridged waveguide tube, the electric fields of the dominant mode are apt to concentrate on the ridge grooves area (Lu and Leonard, 2004). So the ridge grooves deformation would seriously affect the transmission characteristics of double-ridged waveguide tube. Controlling the ridge grooves deformation is the key for obtaining a bended double-ridged waveguide tube part with good transmission characteristics.

Zhao and Cheng (2011) found that the displacement distortion and distortion under stress change the cross sectional shape of rectangular-ridged waveguide, and have large influences on the attenuation characteristics, power-handing capability and impedance characteristics of rectangular-ridged waveguide tube. Sun and Liu (2014) studied the effect of change of ridge grooves shape on the cutoff wavelength of double-ridged waveguide tube using finite element method, which indicates that when the ridge grooves of double-ridged waveguide tube are deformed into ladder-shape or oval-shape, the cutoff wavelength of double-ridged waveguide tube is seriously affected. From the above literature, it can be concluded that the change in shape and size of ridge grooves seriously affect the transmission characteristics of double-

* Corresponding author.
E-mail address: lyl@nwpu.edu.cn (Y. Liu).

http://dx.doi.org/10.1016/j.jmatprotec.2016.12.008
0924-0136/

ridged waveguide tube. So it further demonstrates the importance of studying ridge grooves deformation of double-ridged waveguide tube in rotary draw bending. However, so far, the researches about the cross sectional deformation of double-ridged waveguide tube in rotary draw bending have been scarcely reported in domestic and abroad. Compared with the rectangular tube, the double-ridged waveguide tube just adds ridge grooves, so the studies on the cross sectional deformation of rectangular tube in bending process can provide some guides for the studies on the cross sectional deformation of double-ridged waveguide tube in rotary draw bending. Paulsen and Welo (2001a) experimentally studied the cross-sectional deformation of rectangular tube in bending and found that cross-sectional deformation takes place from the beginning of bending and is in the form of a uniform sagging deformation in the entire deformation region. Then an analytical model to determine the suck-in deformation based on the deformation theory of plasticity with an energy method using appropriate shape functions was developed (Paulsen and Welo, 2001b). Based on the present findings, an approximate design method for evaluating the bendability of tube in industrial forming operations was proposed (Paulsen et al., 2001c). Clausen et al. (1999a) experimentally studied the effect of geometry and tensile force (Clausen et al., 1999b) on the sagging deformation of aluminum extrusions with rectangular hollow section in stretch bending and then analyzed the sensitivity of main parameters on the sagging deformation using the reliable FE model (Clausen et al., 2001). Miller et al. (2001a) experimentally researched the cross sectional deformation of aluminum extruded tube in stretch bending and pointed out internal pressure can reduce distortion for low profile sections and vacuum can reduce distortion for tall sections. Then a simple two-dimensional model was established analytically to investigate the effects of tension, pressure and loading history on the quality of tubes (Miller et al., 2001b). But some 3-D features of stretch bending, such as variations of distortion along the length, the effect of friction and the effect of post-tension, cannot be captured experimentally and analytically. In order to overcome this problem, a 3-D finite element model of stretch bending was then established (Miller and Kyriakides, 2003). Utsumi and Sakaki (2002) applied a combined elastic mandrel and a laminated elastic mandrel to restrain the flattening distortion in the rotary draw bending of extruded square tube. Besides, Zhu et al. (2013) innovatively introduced a PVC mandrel in rotary draw bending of H96 rectangular tube and noted that the PVC mandrel performs much better than the rigid mandrel-cores die on the reduction of height deformation.

For the double-ridged waveguide tube in rotary draw bending, its cross sectional deformation includes not only the flange sagging but the ridge grooves deformation. Some exploratory works on the cross sectional deformation of double-ridged waveguide tube in rotary draw bending were conducted by our team. Liu et al. (2013) studied the cross sectional deformation characteristics of double-ridged waveguide tube in rotary draw bending using the finite element method and pointed out that the width deformation of ridge grooves is severe even if a mandrel was used inside the tube. Li et al. (2014) researched the cross sectional deformation of double-ridged waveguide tube under different parameters of core in rotary draw bending, and found that with the increase of core number and the decrease in the clearance and friction coefficient between mandrel and tube, the flange sagging was improved obviously, but the ridge grooves deformation are still large and even slightly increase. From the works, it can be seen that the flange sagging can be improved effectively when a mandrel was used, but the ridge grooves deformation can not.

So the ridge grooves deformation of double-ridged waveguide tube in rotary draw bending will be studied. The double-ridged waveguide tube includes flanges, webs and ridge grooves, and there is interaction with each other for them in the rotary draw bending.

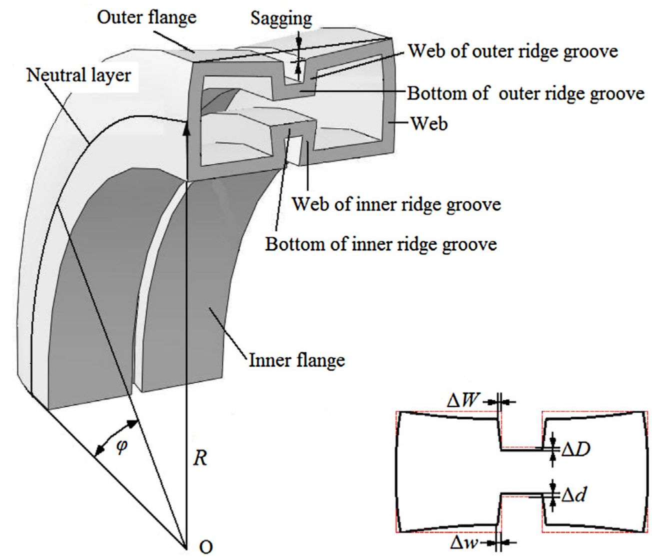

Fig. 1. Schematic illustration of cross sectional deformation of double-ridged waveguide tube in rotary draw bending.

Based on the study on the mechanical analyses and the characteristics of cross sectional deformation of DRWT in rotary draw bending, the ridge grooves deformation is considered to be resulted from flange sagging, web deflection and variation of flange width. Analytical study on the three parts of deformation can learn about the mechanism of ridge grooves deformation deeply. In addition, a reliable FE model of rotary draw bending of double-ridged waveguide tube can be used to verify the analytical method and obtain the comprehensive distribution of ridge grooves deformation for the whole tube. Thus, in order to investigate the ridge grooves deformation of double-ridged waveguide tube in rotary draw bending comprehensively, the analytical method and simulative method are all adopted. Firstly, an analytical method to investigate the ridge grooves deformation is proposed based on the plasticity deformation theory and the analytical method is verified from several aspects by a 3D FE model which is verified by the experiment. Then the ridge grooves deformation law of double-ridged waveguide tube in rotary draw bending is obtained using FE model. Finally, the contribution of every part to the ridge grooves deformation under different conditions are analyzed analytically and simulatively.

2. Analytical study on the ridge grooves deformation of double-ridged waveguide tube in rotary draw bending

2.1. The analysis for the ridge grooves deformation

Double-ridged waveguide tube has relatively complicated profile, including webs, flanges and ridge grooves, as shown in Fig. 1. When the tube is bended to an arc of radius R, except for appearing of flange sagging, the ridge grooves deformation also occurs. The ridge grooves deformation includes the width deformation of outer and inner ridge grooves ΔW and Δw, and the height deformation of ridge grooves ΔD and Δd. But, ΔD and Δd can be improved by adjusting the size of mandrel, so only ΔW and Δw are analyzed in this paper. In the bending process, the tube is in the condition of bending moment M_b, under which the outside and inside of neutral layer for the tube are mainly subjected to the tangent tensile stress and tangent compressive stress σ_φ respectively along the tangent direction i.e. bending direction of longitudinal section, as shown in Fig. 2(a). The tangent stress σ_φ results in the radial resultant stress N_y.